NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3277

SPACE HEATING RATES FOR SOME PREMIXED TURBULENT PROPANE-AIR FLAMES

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Washington
June 1956

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SUMMARY

Measurements of space heating rate can yield information that is useful in characterizing turbulent combustion. For Bunsen burner flames stabilized over a field of pipe-induced turbulence, the space heating rate decreased with increasing linear flow and burner diameter, and was independent of pilot conditions. Calculated space heating rates, at 1-atmosphere pressure, were in the range of 2×10^7 to 6×10^7 Btu per cubic foot per hour. Turbulent burning velocities over the same flow range were correlated by linear velocity at constant burner diameter, but the variation with burner diameter could not be expressed by a simple correlation.

INTRODUCTION

Turbulent combustion has been generally characterized by the turbulent burning velocity U_T, which is commonly defined by the equation

$$U_T = w_v/S_f \tag{1}$$

Previously, this concept has served as the basis of a number of investigations (refs. 1 to 3). (All symbols are defined in the SYMBOLS.) Reference 4, however, proposes that turbulent combustion be characterized by an additional quantity, the space heating rate SHR, which may be defined as

$$SHR = (w_v/v_f)\ (\Delta H_c - \Delta H_r) \tag{2a}$$

In terms of an efficiency factor η, equation (2a) may be written as

$$SHR = (w_v/v_f)\ \eta\ \Delta H_c \tag{2b}$$

Thus, the space heating rate is defined as the product of a space conversion rate w_v/v_f and the quantity of heat released by a unit volume of cold reaction mixture on passing through the flame zone.

The space conversion rate Z, which has dimensions of reciprocal time, is of interest when considered by itself; it is defined in a manner similar to the definition of turbulent burning velocity (eq. (1)).

$$Z = w_v/v_f \tag{3}$$

Thus, $U_T/Z = v_f/S_f$ has dimensions of length and may serve to represent an average flame thickness. Also, if $(\Delta H_c - \Delta H_r)$ is known and constant over a range of conditions, the space conversion rate may itself serve as a characterizing parameter over that range. 3976

As pointed out in reference 4, one advantage of a characterization by space heating rates is that such a characterization is related to the thickness of the turbulent flame brush and the nature of the chemical reaction within the flame zone. These are two distinguishing phenomena about which measurements of turbulent burning velocity give no information. It is true that other investigations (particularly ref. 5) have approached the relation between flame-zone thickness and combustion efficiency from the viewpoint of the wrinkled flame mechanism; however, flame thickness could not be treated quantitatively simply from the measurements of turbulent burning velocity. A second advantage is that the physical meaning of a characterization by space heating rates need not involve the assumption of a particular mechanism of turbulent flame propagation. However, the physical interpretation of a turbulent burning velocity that is based on a mean flame surface seems to require the assumption of a wrinkled flame mechanism (refs. 1 to 3).

As described in reference 4, volumes of turbulent flames stabilized above cylindrical burners were measured and space conversion rates were calculated directly from these. On the basis of chemical and calorimetric analyses of gas samples withdrawn from the outer tip of the turbulent flame brush, it was concluded that all the fuel was consumed in the flame zone (ref. 4). Furthermore, both sets of analyses indicated combustion to equilibrium products for the reaction taking place at a calculated flame temperature. On this basis, space heating rates were obtained. Quantitative treatment of the results did not depend on the assumption of a particular mechanism (ref. 4). The results of reference 4 are summarized in the form of a relation (independent of Reynolds number) among space conversion rate, Reynolds number, burner diameter, and laminar burning velocity

$$Z = 6.1\, U_L/d \tag{4}$$

Since $(\Delta H_c - \Delta H_r)$ (eq. (2a)) remained constant, the space heating rate was proportional to the space conversion rate. These results were compatible with existing concepts of turbulent flame propagation.

This investigation is primarily an extension of reference 4. Measurements were made on the same scale, but over a much larger range of flow conditions, to evaluate critically the concept and its utility, and to investigate directly the generality of equation (4). The apparatus and procedure are similar: piloted turbulent propane-air flames were stabilized above burners in fields of pipe-induced turbulence, and flame volumes were measured visually from negatives of time-exposure photographs. Space conversion and space heating rates were calculated and their behavior examined with respect to changes in stream velocity, burner diameter, laminar burning velocity, and pilot conditions. In addition, turbulent burning velocities were calculated, and the relation between turbulent burning velocity and space conversion rate was examined.

SYMBOLS

The following symbols are used in this report:

A,B,a,b,c	empirical constants
d	burner diameter, cm
ΔH_c	heat of combustion per unit volume to give carbon dioxide and water, Btu/cu ft
ΔH_r	residual heating value, per unit volume consumed, of exhaust products, Btu/cu ft
h	flame height, cm
I	total radiation intensity, volts
l	mean flame thickness, cm
Re	Reynolds number
S	surface, sq cm
SHR	space heating rate, Btu/cu ft-hr
U	burning velocity, cm/sec
V	average linear velocity, cm/sec
v_f	volume of flame brush, cc
w	flow rate, cc/sec

Z space conversion rate, sec^{-1}

η efficiency

ν kinematic viscosity, sq cm/sec

Φ equivalence ratio; percent fuel divided by percent fuel for a stoichiometric mixture

Subscripts: 3976

f flame

i inner cone

L laminar

o outer cone

T turbulent

v volume

APPARATUS AND PROCEDURE

Burners

Two burners were used in this study: One burner was the same burner used in references 4 and 6. The other burner was of similar design, but larger. Both burners had water jackets near the lip and length-to-diameter ratios within the pipe greater than 60 (ref. 6). Turbulent flames were stabilized above the burner lip by a small annular pilot flame.

In the smaller burner, the pilot annulus had a diameter of 2 centimeters and the main tube, a diameter of 1.890 centimeters. The effective diameter of the main burner tube could be varied by means of tubular inserts. Actually, inserts of 0.639-, 1.016-, and 1.459-centimeter diameter were used. In the larger burner, the pilot annulus had a diameter of 3.3 centimeters and the main tube, a diameter of 3.18 centimeters. Inserts of 0.93-, 1.95-, and 2.55-centimeter diameter were used in the larger burner. One result of using two separate burner systems was that the annulus-to-burner diameter ratio could be varied without significant change in the burner diameter.

Flow System

The flow system used was similar to that described in references 4 and 6, but was designed to accommodate much larger flows. Furthermore, the pilot system was completely separate, so that pilot flow and composition could be varied independently of the main burner flow. In both systems, gas flow was regulated by calibrated critical flow orifices; fuel and oxidant were metered separately and then mixed. In the main burner system, total flows of 1000 to 30,000 cubic centimeters per second were used; in the pilot system, flows of 50 to 250 cubic centimeters per second were used. Within the range of experimental conditions, corrections in observed volume flows for fluctuations of temperature and pressure were negligible. A sketch of the flow systems is given in figure 1.

Mixture Conditions

In general, stoichiometric propane-air flames were studied although, for one series of experiments, the fuel-air ratio was varied at constant Reynolds number. The pilot flow and composition were adjusted to maintain a stable flame. At lower flows, a propane-air pilot sufficed to stabilize a flame; at higher flows, it was necessary to enrich the pilot flow with oxygen. In both burner systems, propane (c.p.), oxygen, and service air were used.

Measurement of Space Conversion Rates

Flames were photographed with a view camera using 5- by 7-inch film at magnifications of about 0.3 to 1.3, according to the height of the flame. Flame volumes were measured from negatives of time-exposure photographs of stabilized turbulent flames by the procedure of reference 4. Detailed dimensions of the flame zone were recorded, corrected for magnification, and plotted. The volume was calculated by subdivision of the flame zone into appropriate geometric segments and by integration of the individual segments. Varying exposure time between 1 and 1/5 second at apertures between f/5 and f/16 did not appreciably affect the measured flame volumes. After the volume was measured, the space-conversion rate was obtained from equation (3).

Measurement of Turbulent Burning Velocities

The mean flame surface, measured as the surface midway between the outer and inner flame envelopes, was obtained from the same negatives that were used for volume determination. It was located by visual estimation, subdivided into geometric segments, and its value calculated by graphical integration. The turbulent burning velocity was then obtained from equation (1).

Analysis of Exhaust Gases

The value of $(\Delta H_c - \Delta H_r)$ in equation (2b) was determined (as in ref. 4) by measurement of the residual heating value of gaseous combustion products withdrawn from the upper part of the outer envelope of a turbulent flame brush by means of a water-cooled probe with an orifice opening. The apparatus used was a flow calorimeter, which is described in detail in reference 7. Exhaust products were dried, passed through an adiabatic reactor at a known flow rate, and catalytically oxidized at about 550° C to carbon dioxide and water. The temperature rise (usually about 50° C) was compared with that observed when a suitable mixture having a known heating value was passed through the reactor at the same flow rate. In this way, the value of ΔH_r was determined.

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RESULTS

Residual Heat Values

Direct calorimetric analysis of exhaust products from the outer tip of the flame brush gave residual heat values ΔH_r of 4 to 6 Btu per cubic foot (0.8 to 1.2 kcal/mole). This value may be compared with the total heat of combustion of a stoichiometric propane-air mixture, which is about 93 Btu per cubic foot (about 19 kcal/mole), net.

Flames were probed at Reynolds numbers between 10,000 and 50,000, corresponding to linear velocities of 800 to 7000 centimeters per second. Burners of 0.93- and 1.95-centimeter diameter were used. All values are within the limits given previously. However, the lower values were obtained consistently at higher linear flow rates. In reference 4, about 5 Btu per cubic foot were obtained at lower flows, which agreed closely with the residual heat value calculated for combustion to equilibrium products. Within the estimated accuracy of the technique (±1 Btu/cu ft) the results of this investigation also indicated combustion to equilibrium across the flame zone. Therefore, $(\Delta H_c - \Delta H_r)$ may be considered constant and equal to 88 ±1 Btu per cubic foot.

The observed residual heat value was quite sensitive to the position of the probe. If the probe was lowered about 1/2 inch from the estimated tip position for a total flame height of about 12 inches, a residual heat value of about 17 Btu per cubic foot was obtained. The good reproducibility obtained with samples withdrawn from the tip position over a range of flame heights and burner diameters indicated that the probe was correctly positioned in those cases. Moreover, chemical analyses (ref. 4) have shown that ambient air was not drawn into the probe.

In one case, a sample was withdrawn from a lower position and analyzed by conventional gas analysis methods. The result showed a concentration of hydrocarbon equal to about 15 percent of the inlet propane concentration, which indicated that the quenching action within the probe was sufficient to ensure that measurable quantities of hydrocarbon would pass through without reacting. Therefore, the presence of hydrocarbon in an exhaust sample would give an abnormally large residual heat value.

Space Conversion and Space Heating Rates

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Experimental space conversion rates and turbulent burning velocities are shown in table I and figure 2 as a function of Reynolds number. Reynolds number served as a convenient correlating flow parameter and was calculated in the manner of reference 6:

$$Re = V\ d/\nu \tag{5}$$

For the systems considered in this report, the kinematic viscosity ν was equal to 0.15 square centimeter per second. The space conversion rate was found to be independent of pilot flow and composition and was unaffected by changes in the ratio of pilot annulus to burner diameter. As a further experimental check, a series of measurements was made with the same flow system which was used in reference 4 (small flow system, figs. 2(b), (c), and (d)). The results were consistent with those obtained at higher flows in the larger flow system.

Space heating rates were calculated from equation (2a). These rates are between 2×10^7 and 6×10^7 Btu per cubic foot per hour at 1-atmosphere pressure. That is, they are about an order of magnitude lower than values reported for laminar flames (ref. 4).

The scatter of points is about the same as reported in reference 4 (±10 percent). Comparison of these results with those of reference 4 shows that values in this report for space conversion rates are somewhat lower. This deviation is principally due to differences in the choice of flame boundaries. Because of this deviation, it was impossible to draw conclusions other than those regarding data trends.

Turbulent Burning Velocities

The turbulent burning velocities in table I are considered as functions of Reynolds number to facilitate comparison with previous work. These values are consistent with those previously reported (refs. 6 and 8).

DISCUSSION

Space Conversion Rate

Effects of flow. - The space conversion rate decreases with increasing flow for a particular burner diameter up to a Reynolds number of about 60,000 (fig. 2). At higher flows, the space conversion rate seems to be independent of flow, although the number of measurements at these higher flows may not be sufficient to establish a clear trend. That portion of the data for which $Re \leq 60{,}000$ may be correlated by the equation

$$Z = 189 - 27.3d - 0.881\times10^{-3}\ Re \tag{6a}$$

under the assumption that the initial decrease of space conversion rate is linear with Reynolds number. Plots of equations (6) are shown as solid lines in figure 2. The coefficients were obtained by first fitting the data for all six burner sizes as linear functions of Reynolds number

$$Z = A + BRe \tag{6b}$$

Then, the coefficients A and B were expressed as functions of burner diameter. It should be noted that, if flow is expressed as Reynolds number, the coefficient B is independent of burner diameter. An alternate correlation, which takes into account all the data, has the form

$$\log Z = 3.01 - (0.170 + 0.0268d) \log Re \tag{7}$$

The observed decrease of space conversion rate with flow corresponds to a faster increase in flame volume with increasing flow than would be represented by a simple proportionality. Visually, this relation takes the form of increased spreading and diffuseness in the upper portion of the flame brush. Figure 3 shows that the rate of change of the outer cone height decreases with increasing flow, thus suggesting that the bulk of the spreading occurs laterally.

The over-all appearance of a turbulent Bunsen burner flame also changes with flow. At linear velocities below 2500 centimeters per second, the flame brush is surrounded by a distinct pale blue mantle, which is visible to the eye and discernible on a normal photograph taken with panchromatic film. For such flames, the maximum diameter of the outer cone of the brush is found at or near the base of the flame. If the linear velocity is greater than about 4000 centimeters per second, however, one cannot detect any boundary between the flame brush and the mantle; rather, the two merge into a single diffuse combustion zone. Moreover, the maximum brush diameter occurs at about the top of the inner cone. This behavior indicates, perhaps, an increase in the scale of turbulence within the flame zone with increasing flow. However, it has been shown that for the case of a free-air jet issuing from a nozzle, the longitudinal scale at a point in the jet is independent of the average linear velocity at the nozzle exit (ref. 9).

The observed decrease in space conversion rate with flow may be related to the increase in flame thickness or reaction length. The flame thickness increased more rapidly with increasing flow than it would if the space conversion rate were constant. This indicates that, at high flow rates, a mass of combustible mixture requires, on the average, a longer time to be consumed completely than at low flow rates; thus, a lower reaction rate prevails at high flow rates than at low flow rates. The simplest possible explanation of this situation involves a lower flame temperature, averaged over time and space, with increasing flow.

No measurements of flame temperatures across a turbulent brush which are applicable to this situation have been reported; hence, a direct check is impossible. However, some experimental evidence may be offered which, although inconclusive, is consistent with a hypothesis of a lower effective flame temperature: A series of measurements of total radiation intensity was made with a simple direct current photomultiplier unit. The results are shown in figure 4 (intensity is expressed in voltage output). The rate of change of intensity with flow decreased with increased flow. This indicates that, on the average, a unit volume of combustible mixture emits less radiation on passage through the flame zone with increasing flow. This decrease in radiation could represent the result of a lower average flame temperature. However, it might also represent a change in the nature of the reaction within the flame zone.

It should be noted that the dependence of space conversion rate on Reynolds number observed in reference 4, in which Z was reported to be independent of Reynolds number, is consistent with results of this report. The measurements reported in reference 4 covered a relatively small flow range, so that trends observed over a wider flow range were not apparent.

Effects of burner diameter. - Equations (7) and (more clearly) (6a) show that the space conversion rate decreases with increasing burner diameter either at constant Reynolds number or linear velocity. The magnitude of this trend is smaller than reported in reference 4; however, its direction remains the same. These results suggest that the efficiency of space conversion decreases with increasing scale of approach-stream turbulence.

Effect of laminar burning velocity. - In reference 4, the laminar burning velocity was varied by enriching the fuel-air mixture with oxygen while maintaining a stoichiometric fuel-oxygen ratio. Results showed that the space conversion rate was proportional to the laminar burning velocity. In this work, the laminar burning velocity was changed by varying the equivalence ratio of fuel-air mixtures. The results are shown in figure 5 in which measured space conversion rates and turbulent burning velocities are plotted as functions of equivalence ratio along with the laminar burning velocities reported in reference 6. In this case, the space conversion rate does not bear a simple relation to the laminar burning velocity, but more closely follows the behavior of the turbulent burning velocity. Thus, the laminar burning velocity peaks at an equivalence ratio of about $\Phi = 1.05$, whereas both space conversion rates and turbulent burning velocities peak at about $\Phi = 1.4$. The behavior of the turbulent burning velocities is consistent with the observation that turbulent burning velocities for butane-air mixtures peak quite rich of stoichiometric (ref. 10).

Turbulent Burning Velocities

An attempt was made to correlate observed turbulent burning velocities by an equation of the form (ref. 8)

$$U_T = a\ Re^b\ d^c \tag{8}$$

Previous investigations, which covered a smaller range of flows, showed that the exponent b was about 0.25; c was a constant which had a value of zero or 0.25, depending on the observer (refs. 6 and 8). Analysis of the present data, however, indicates that both b and c are functions of burner diameter and, therefore, a simple correlation in the form of equation (8) cannot be applied. However, for a given burner diameter, the data are well correlated by either Reynolds number or linear velocity. Therefore, data for each burner have been fitted by the method of least squares to equations of the form

$$U_T = a' Re^{b'} \tag{9}$$

where a' and b' are different for different burners. These curves are plotted in figure 2. Numerical agreement with previous work was generally satisfactory; however, trends previously reported were not followed when measurements were made over a longer flow range.

The data of reference 6 are not shown in figure 2. The results for a burner diameter of 1.890 centimeters are in agreement with present results. However, for $d = 1.016$ centimeters and $d = 0.639$ centimeter, the results of reference 6 are consistently about 25 percent higher than present results. This disagreement is probably due to the fact that (in ref. 6) the mean flame surfaces are computed by a different approximation.

Comparison of Concepts

Although it seems that a characterization in terms of space heating and space conversion rates is more meaningful and potentially more useful than one in terms of turbulent burning velocities, its application is limited by the lack of a satisfactory definition of the boundaries of a turbulent flame brush. On the other hand, although measurements of turbulent burning velocity are experimentally convenient and values are more nearly reproducible among observers, the physical meaning of a turbulent burning velocity based on a mean flame surface is not clear. Thus, interpretation of turbulent burning velocities in terms of a wrinkled flame mechanism assumes that the mean flame surface is nearly coincident with the surface of maximum luminosity. However, the surface of maximum luminosity is discontinuous; below the top of the inner cone, the surface of maximum luminosity has the general shape of a frustum of a cone; above it, the surface of maximum luminosity is a straight line coincident with the flame axis. Actually, the mean flame surface above the tip of the inner cone must be approximated in some fashion; in this study, it was computed as a paraboloid of revolution whose base was the circle of maximum luminosity at the top of the inner cone and whose height was taken to be $(h_o - h_i)/2$. Thus, for diffuse Bunsen burner flames at high velocities, where the distance between the tops of the inner and outer cones is an appreciable fraction of the total height, the mean flame surface is significantly different from the surface of maximum luminosity. In these cases, turbulent burning velocity does not have physical meaning even in terms of a wrinkled flame mechanism. On the basis of measurements of this investigation, it is of interest to consider an average flame brush thickness, which may be defined by the equation

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$$l = U_T/Z \tag{10}$$

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Such an average flame thickness increases with increasing flow and burner diameter at a rate slightly faster than the corresponding rate of decrease of Z (table I). The utility of equation (10) is severely limited, however, by the large absolute uncertainty in Z, and its application does not give a reliable value for the average flame thickness.

CONCLUDING REMARKS

Space heating and space conversion rates are desirable parameters for characterizing turbulent combustion. The application of such a characterization to turbulent Bunsen burner flames is limited, however, by the difficulty of defining and measuring the volume of a turbulent flame brush.

For Bunsen burner flames with pipe turbulence, the space heating rate decreases linearly with flow velocities and burner diameter at constant density, viscosity, and equivalence ratio. For the same range of conditions, the turbulent burning velocity, by contrast, increases with increasing flow velocity for a given burner diameter. However, the turbulent burning velocity is not found to correlate in a simple fashion with the burner diameter.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 28, 1956

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TABLE I. - MEASUREMENTS ON TURBULENT FLAMES

Reynolds number, Re	Flame outer cone height, h_o, cm	Flame inner cone height, h_i, cm	Volume of flame brush, v_f, cm	Space conversion rate, Z, 1/sec	Turbulent burning velocity, U_T, cm/sec	Equivalence ratio, Φ
Burner diam., 0.639 cm						
20,200	17.6	12.6	10.1	151	50.2	1.0
20,200	17.4	12.0	9.72	158	54.7	
24,900	18.8	13.5	10.9	172	59.9	
24,900	19.2	13.5	12.6	149	54.9	
29,600	20.3	14.9	16.8	132	56.2	
29,600	20.6	14.9	16.2	137	55.1	
38,500	21.1	15.7	18.0	144	63.0	
38,500	23.0	14.7	16.2	145	64.2	
44,500	21.8	16.0	24.0	139	66.4	
Burner diam., 1.016 cm						
10,700	12.1	9.15	8.72	149	48.7	1.0
13,500	13.1	10.4	10.8	152	55.6	
14,200	12.7	9.6	11.9	144	57.4	
18,600	17.3	13.3	15.4	146	55.7	
18,600	17.1	12.0	16.0	139	54.9	
27,900	21.9	15.6	25.0	133	55.0	
27,900	22.7	15.9	26.2	127	55.0	
37,300	26.9	19.9	35.7	124	61.1	
37,300	25.2	18.0	34.2	130	68.6	
46,600	28.1	21.0	41.5	133	74.3	
55,800	31.2	21.7	57.9	115	75.5	
55,800	30.3	21.2	58.6	114	75.2	
65,200	31.4	22.5	70.6	110	79.7	
65,200	32.1	24.5	66.9	116	76.9	
74,500	32.9	23.5	72.0	123	86.7	
74,500	34.1	24.0	70.0	127	87.9	
83,900	35.1	23.6	76.4	130	92.9	

TABLE I. - Continued. MEASUREMENTS ON TURBULENT FLAMES

Reynolds number, Re	Flame outer cone height, h_o, cm	Flame inner cone height, h_i, cm	Volume of flame brush, v_f, cm	Space conversion rate, Z, 1/sec	Turbulent burning velocity, U_T, cm/sec	Equivalence ratio, Φ
Burner diam., 1.459 cm						
7,480	8.91	6.25	8.50	153	55.7	1.0
9,440	10.4	7.16	11.11	148	58.4	
13,280	13.0	9.54	16.0	144	62.0	
13,000	12.9	9.4	17.8	124	56.4	
13,000	12.4	9.0	18.3	121	61.7	
19,500	17.4	12.4	28.9	115	62.8	
19,500	17.7	13.6	28.2	118	60.9	
26,000	21.3	15.4	38.1	108	62.9	
26,000	21.8	16.2	32.7	135	67.6	
26,000	19.6	14.9	31.3	139	70.5	
32,500	24.3	17.3	40.0	137	77.0	
39,000	28.9	20.5	69.4	96	66.1	
39,000	28.8	20.1	66.5	100	68.4	
45,500	31.7	22.2	73.1	105	70.0	
45,500	31.8	23.8	72.7	107	68.8	
45,500	31.0	21.7	74.1	105	72.1	
52,000	33.0	23.4	77.3	115	79.4	
52,000	34.9	24.3	94	95	72.6	
58,500	36.7	24.6	97.5	103	83.3	
58,500	34.3	25.4	79.9	125	80.1	
65,000	36.8	26.3	116.2	96	77.7	
65,000	39.0	27.0	101	110	81.7	
71,500	37.6	27.8	132	92	77.3	
87,300	47.2	29.2	197	76	82.4	
98,000	48.8	30.4	210	80	88.6	

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TABLE I. - Continued. MEASUREMENTS ON TURBULENT FLAMES

Reynolds number, Re	Flame outer cone height, h_o, cm	Flame inner cone height, h_i, cm	Volume of flame brush, v_f, cm	Space conversion rate, Z, 1/sec	Turbulent burning velocity, U_T, cm/sec	Equivalence ratio, Φ
Burner diam., 1.890 cm						
5,760	6.86	4.61	9.75	133	59.7	1.0
7,280	8.0	5.16	11.8	144	65.8	
7,730	7.7	5.5	11.4	147	66.5	
10,210	9.88	6.90	14.5	159	71.1	
10,000	9.3	6.2	15.8	144	66.5	
10,000	9.8	7.8	16.5	139	62.7	
10,000	9.7	6.3	15.4	148	63.6	
10,000	9.1	6.4	18.0	120	69.4	
15,000	13.4	10.4	25.6	133	62.7	
15,000	13.4	10.0	26.7	125	65.6	
15,000	12.9	9.5	26.8	124	69.1	
15,000	14.0	8.4	26.4	129	63.6	
20,000	15.1	10.7	28.6	159	74.7	
20,000	15.6	12.2	34.1	130	73.8	
20,000	14.6	11.1	30.4	146	79.4	
20,000	15.0	10.7	31.9	143	75.0	
25,000	18.9	13.0	47.4	120	68.7	
25,000	18.9	13.0	48.4	117	69.4	
30,000	20.4	15.5	56.6	118	78.6	
30,000	22.4	15.6	59.5	112	75.9	
35,000	25.0	17.0	61.6	126	81.5	
35,000	22.7	17.1	68.1	114	79.9	
35,000	24.8	17.4	70.5	110	76.6	
40,000	29.1	20.0	83.0	107	75.3	
40,000	25.9	20.7	79.0	112	76.8	
45,000	29.5	22.9	102	98	77.4	
45,000	29.7	22.3	101	96	78.8	
45,000	31.0	22.7	111	90	72.8	
50,000	33.6	22.7	124	90	79.9	
50,000	32.4	26.2	132	85	71.9	
55,000	34.8	26.1	153	80	76.2	
75,300	43.5	29.6	171	98	90.7	
83,700	48.4	30.7	236	79	90.0	
92,000	49.5	32.3	272	76	93.0	
92,000	45.7	32.3	227	91	87.7	
101,000	53.0	35.0	266	84	92.2	

TABLE I. - Concluded. MEASUREMENTS ON TURBULENT FLAMES

Reynolds number, Re	Flame outer cone height, h_o, cm	Flame inner cone height, h_i, cm	Volume of flame brush, v_f, cm	Space conversion rate, Z, 1/sec	Turbulent burning velocity, U_T, cm/sec	Equivalence ratio, Φ
Burner diam., 2.55 cm						
12,600	12.7	8.7	41	92	64.4	1.0
18,800	16.1	11.1	54	104	74.8	
25,000	18.3	13.7	76	98	80.1	
31,400	21.7	14.3	116	81	82.3	
37,700	24.4	17.1	130	86	91.3	
50,000	33.9	24.4	204	63	75.3	
Burner diam., 3.18 cm						
10,000	9.7	6.6	38	99	71.1	1.0
10,000	9.9	6.7	41	92	68.5	
15,000	12.9	8.9	54	104	79.9	
15,000	11.9	8.3	64.2	88	80.4	
15,000	11.6	8.2	58	97	83.7	
20,000	16.1	10.5	93.5	80	82.0	
20,000	16.2	11.4	81.6	92	77.8	
25,000	23.2	16.8	124	76	68.0	
25,000	22.0	14.6	137	69	71.7	
35,000	32.0	24.6	180	73	68.8	
45,000	34.1	22.8	240	73	78.7	
45,000	32.6	20.2	226	75	80.9	
50,000	55.5	35.4	458	41	52.5	.8
50,000	35.2	24.3	334	56	76.7	1.0
50,000	35.3	23.7	315	59	76.2	1.0
50,000	27.4	17.7	223	81	108	1.2
50,000	26.5	18.8	199	94	108	1.4
50,000	27.2	18.5	217	86	103	1.6
55,000	37.8	21.2	273	59	84.4	1.0
60,000	41.0	24.6	404	56	82.8	
70,000	43.7	26.8	479	55	86.4	

3976

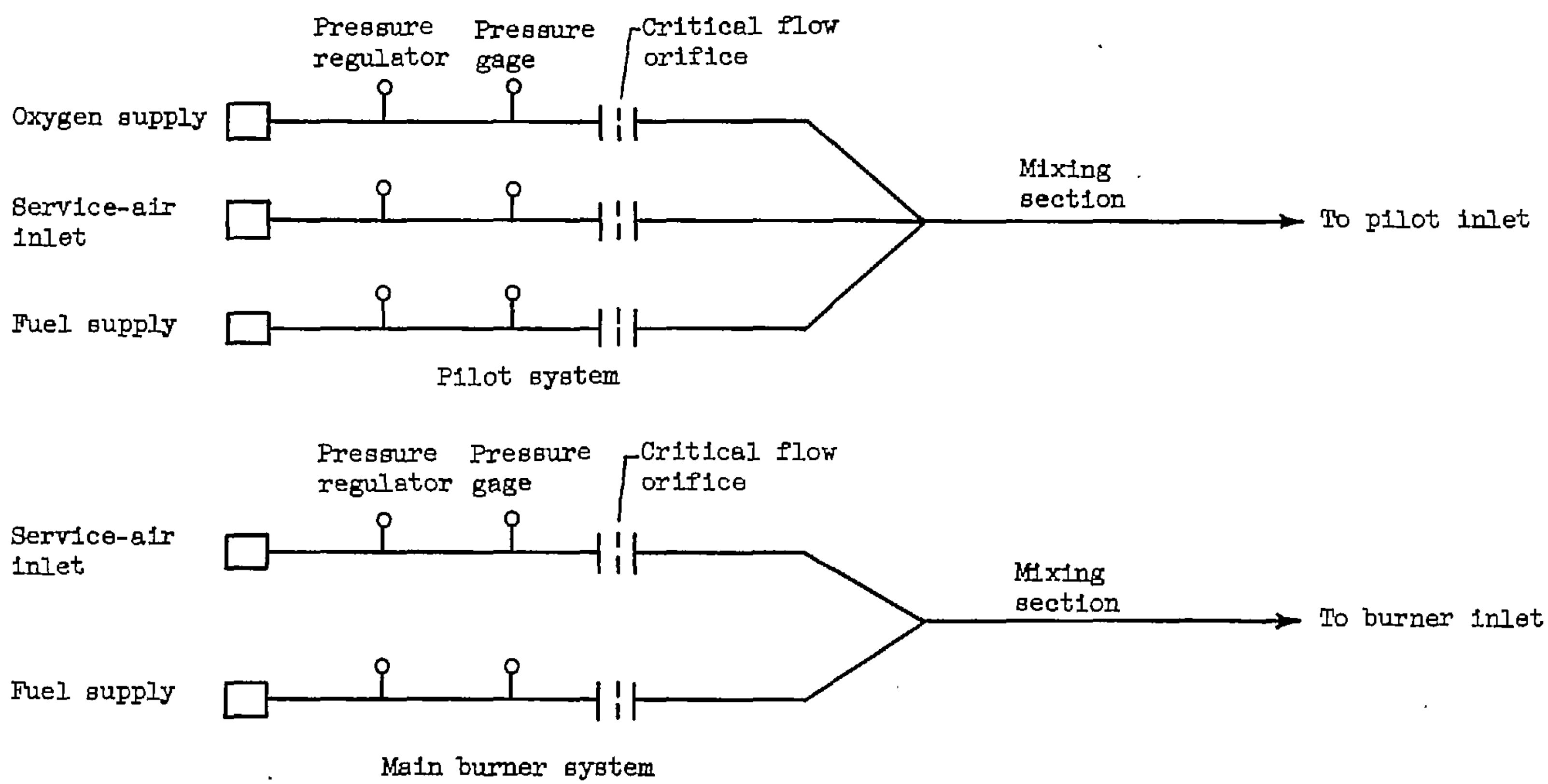
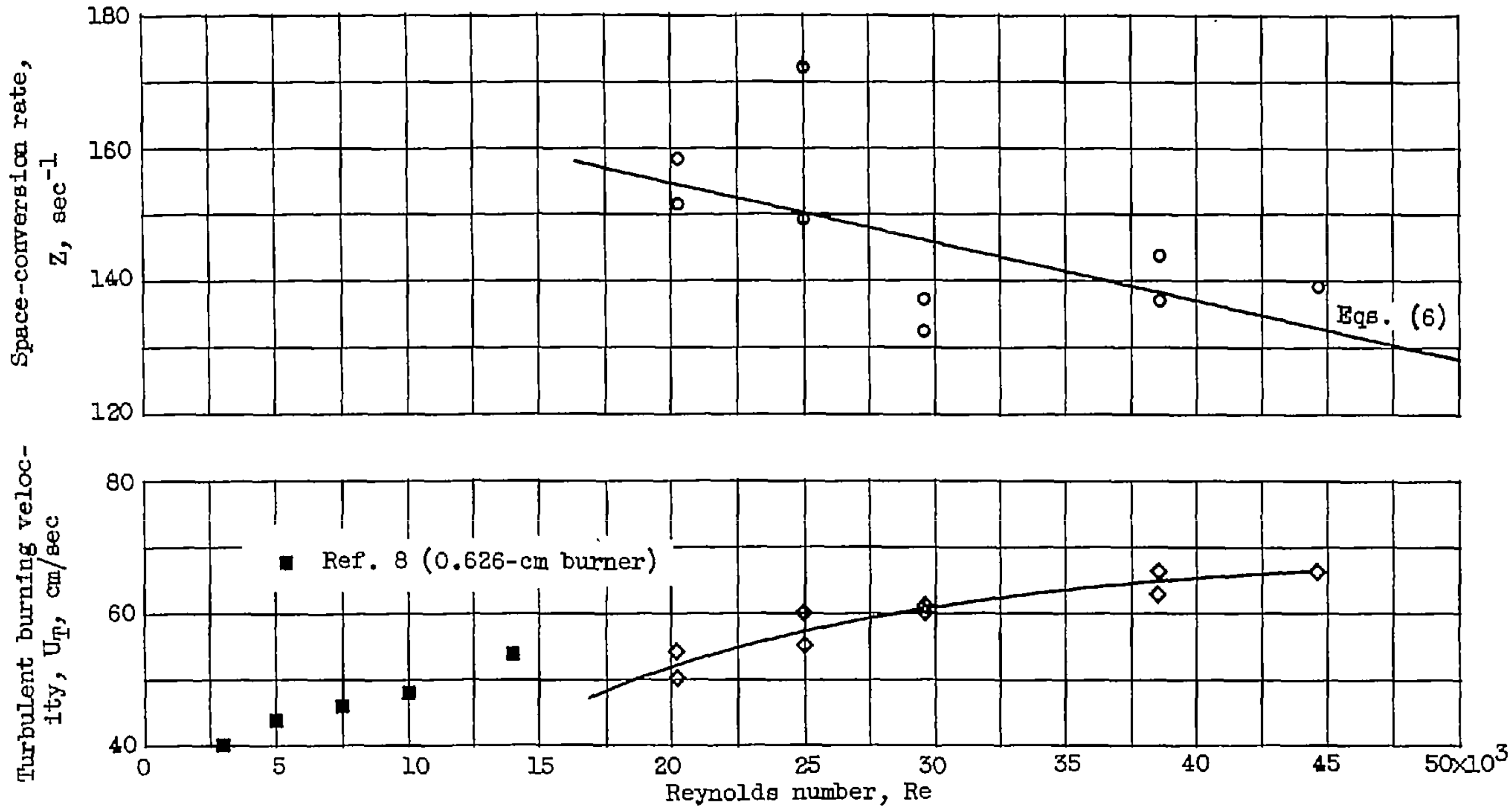


Figure 1. - Flow system.

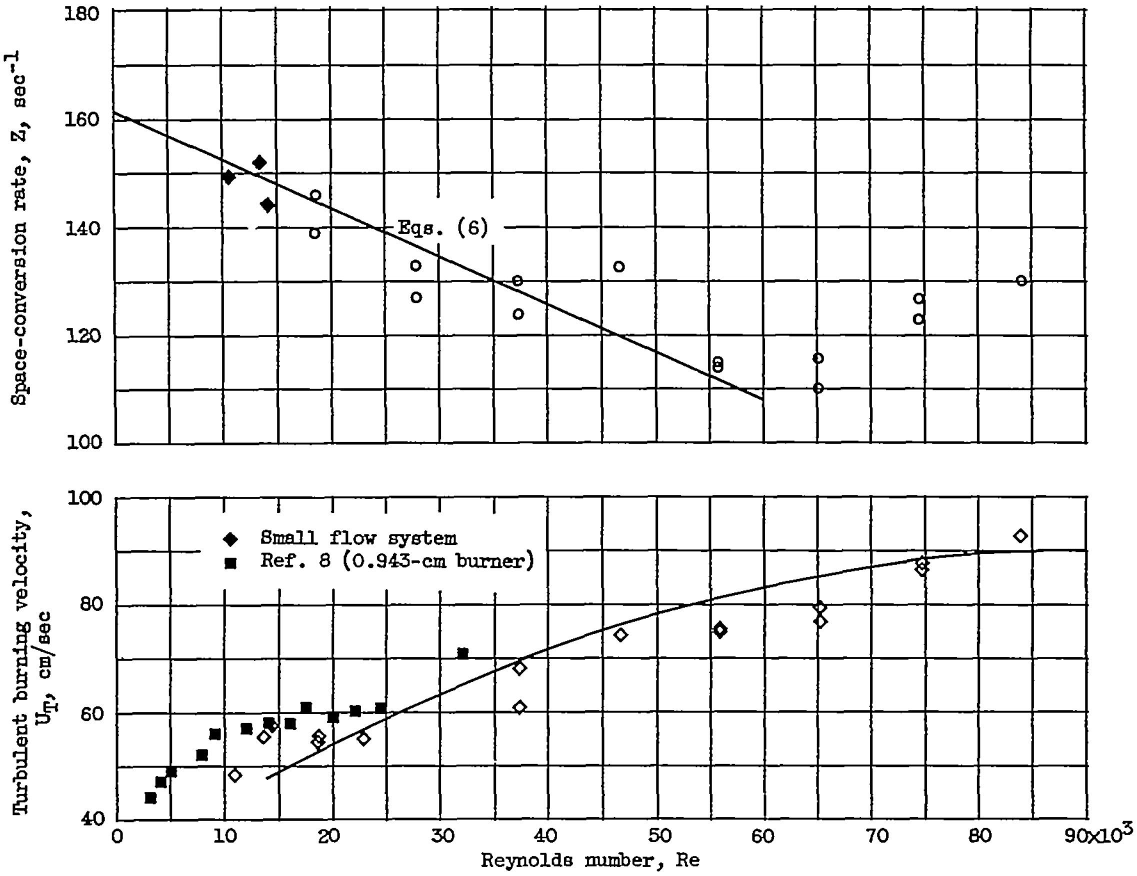


(a) Burner diameter, 0.639 centimeter.

Figure 2. - Space conversion rates and turbulent burning velocities as functions of Reynolds number.

3976

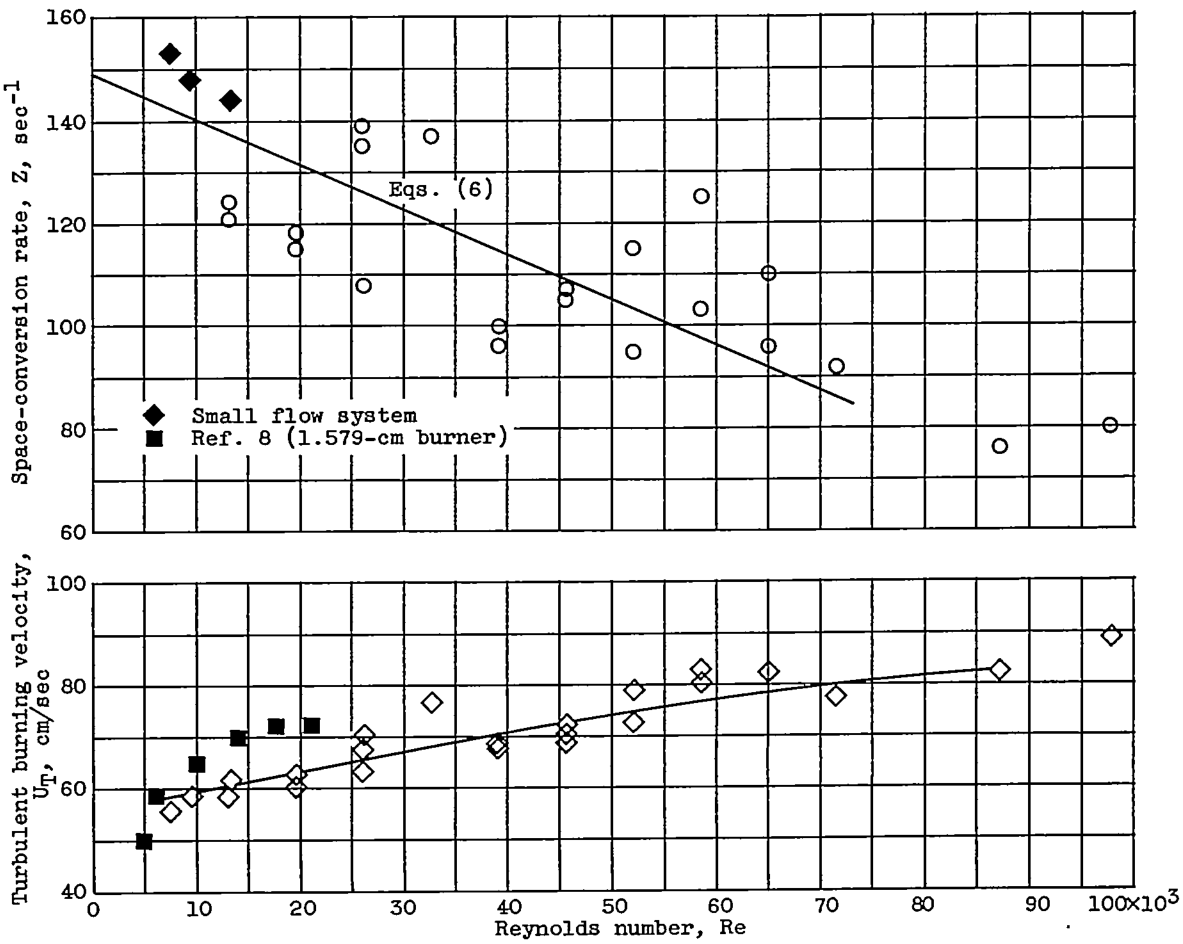
CB-3 back



(b) Burner diameter, 1.016 centimeters.

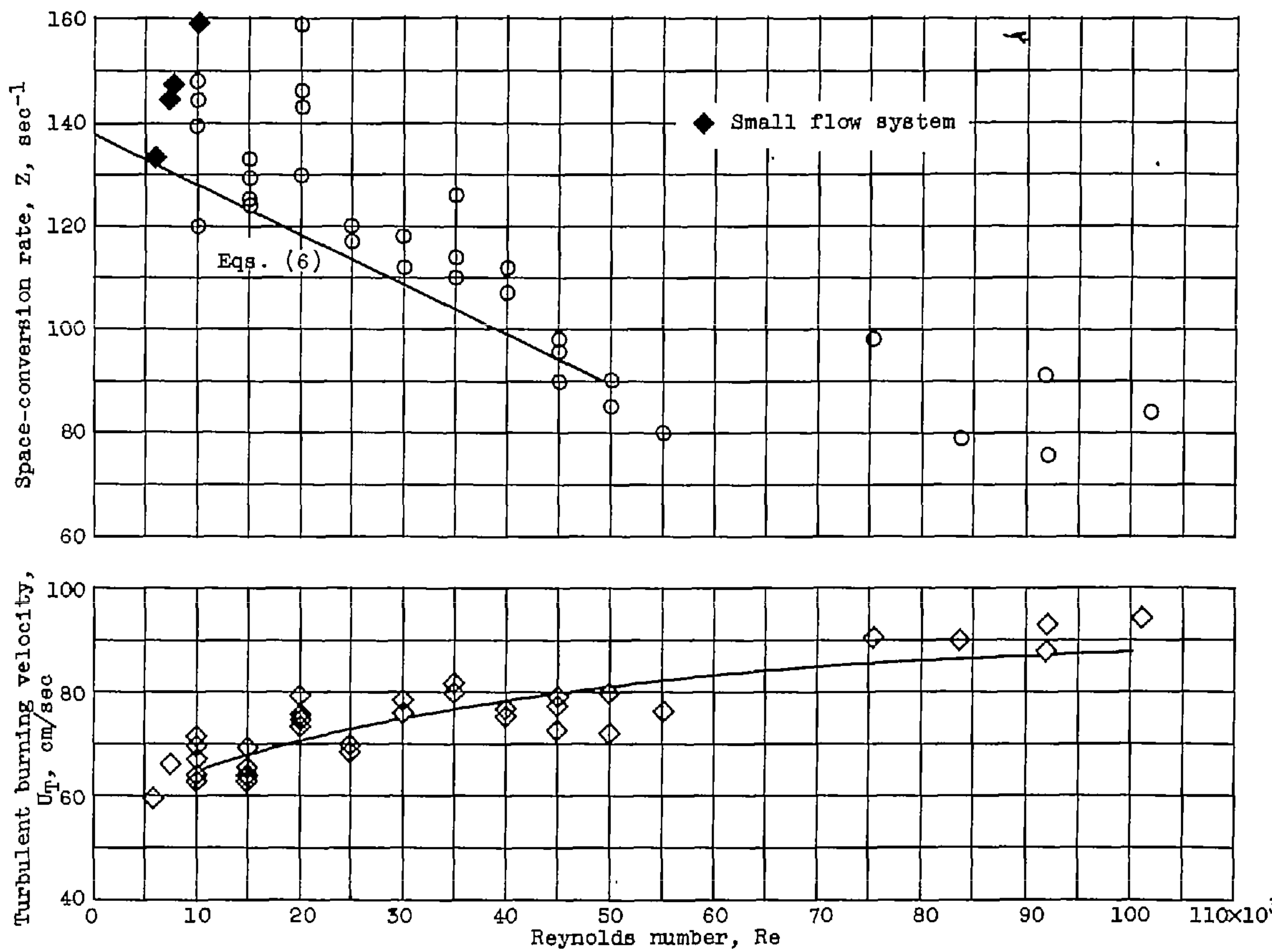
Figure 2. - Continued. Space conversion rates and turbulent burning velocities as functions of Reynolds number.

3976



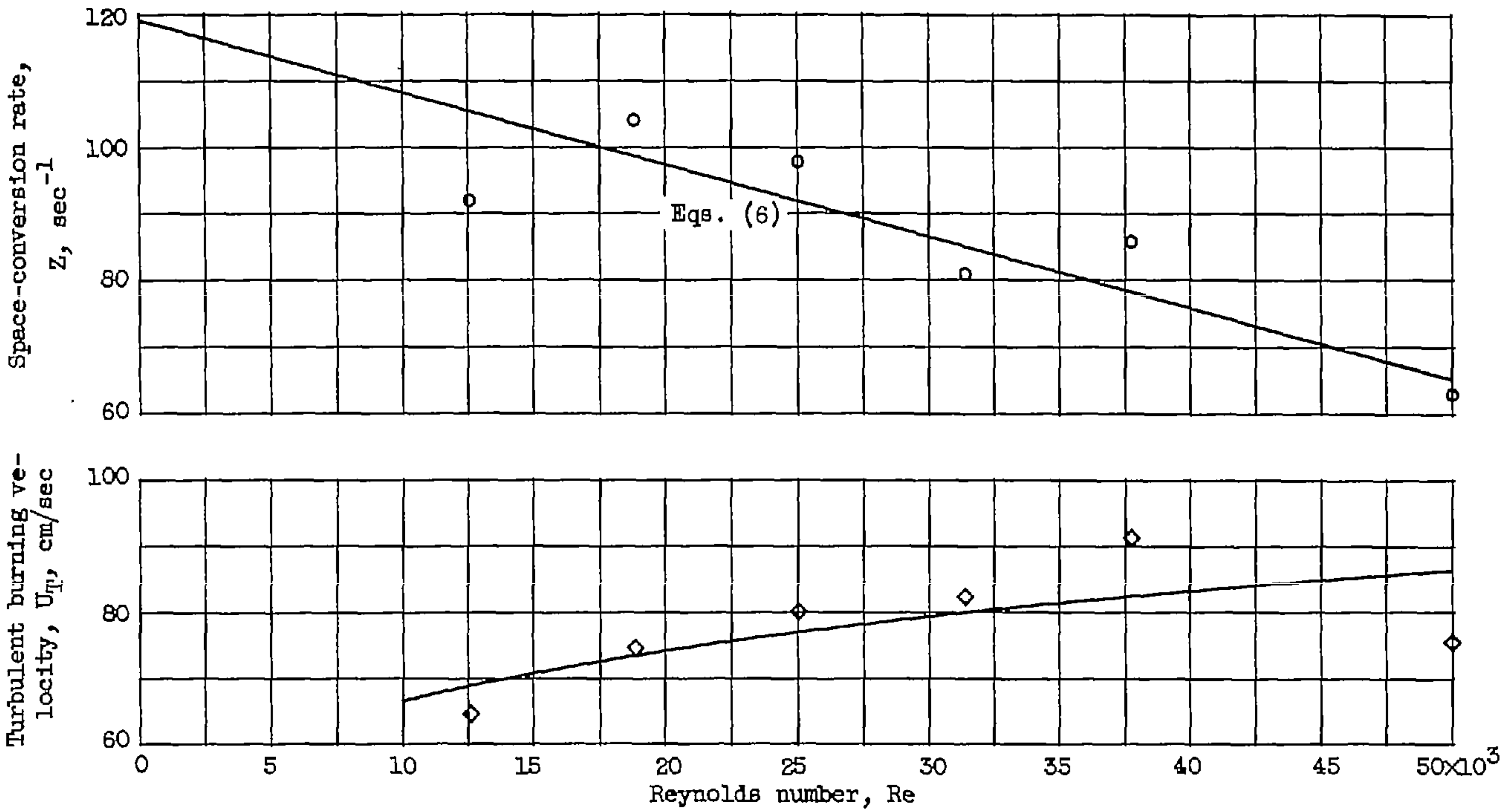
(c) Burner diameter, 1.459 centimeters.

Figure 2. - Continued. Space conversion rates and turbulent burning velocities as functions of Reynolds number.



(d) Burner diameter, 1.890 centimeters.

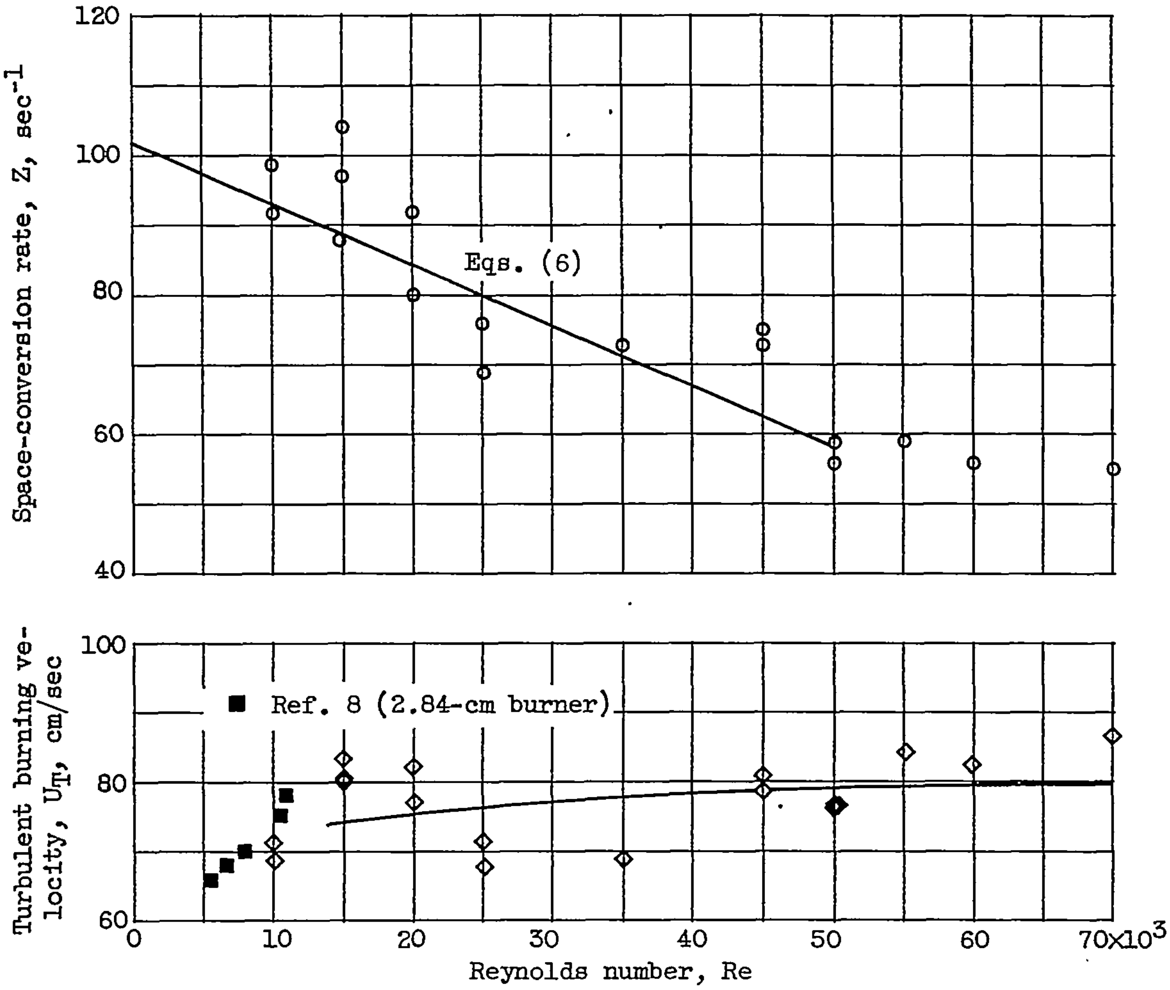
Figure 2. - Continued. Space conversion rates and turbulent burning velocities as functions of Reynolds number.



(e) Burner diameter, 2.55 centimeters.

Figure 2. - Continued. Space conversion rates and turbulent burning velocities as functions of Reynolds number.

3976



(f) Burner diameter, 3.18 centimeters.

Figure 2. - Concluded. Space conversion rates and turbulent burning velocities as functions of Reynolds number.

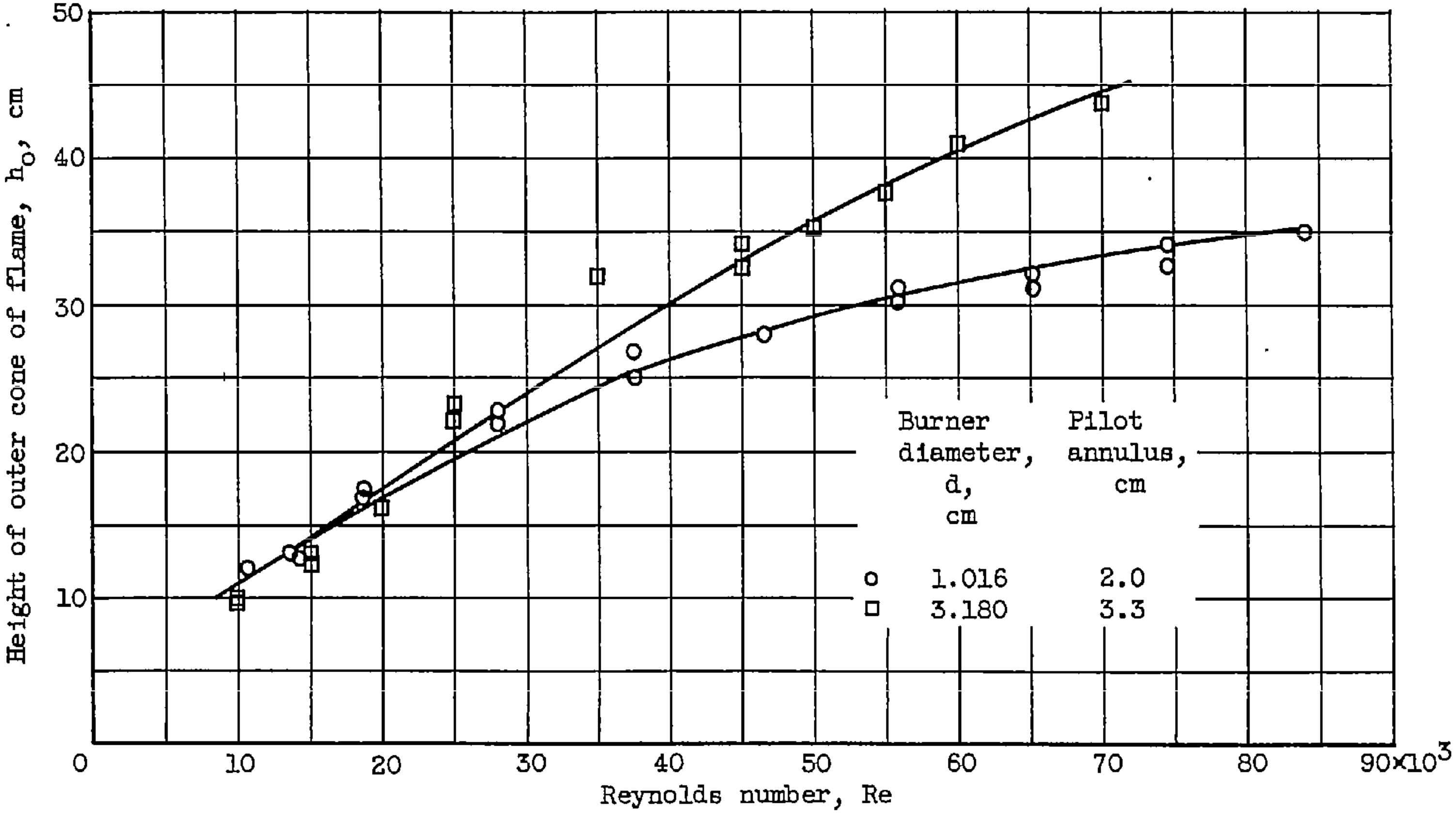


Figure 3. - Height of outer cone as a function of Reynolds number.

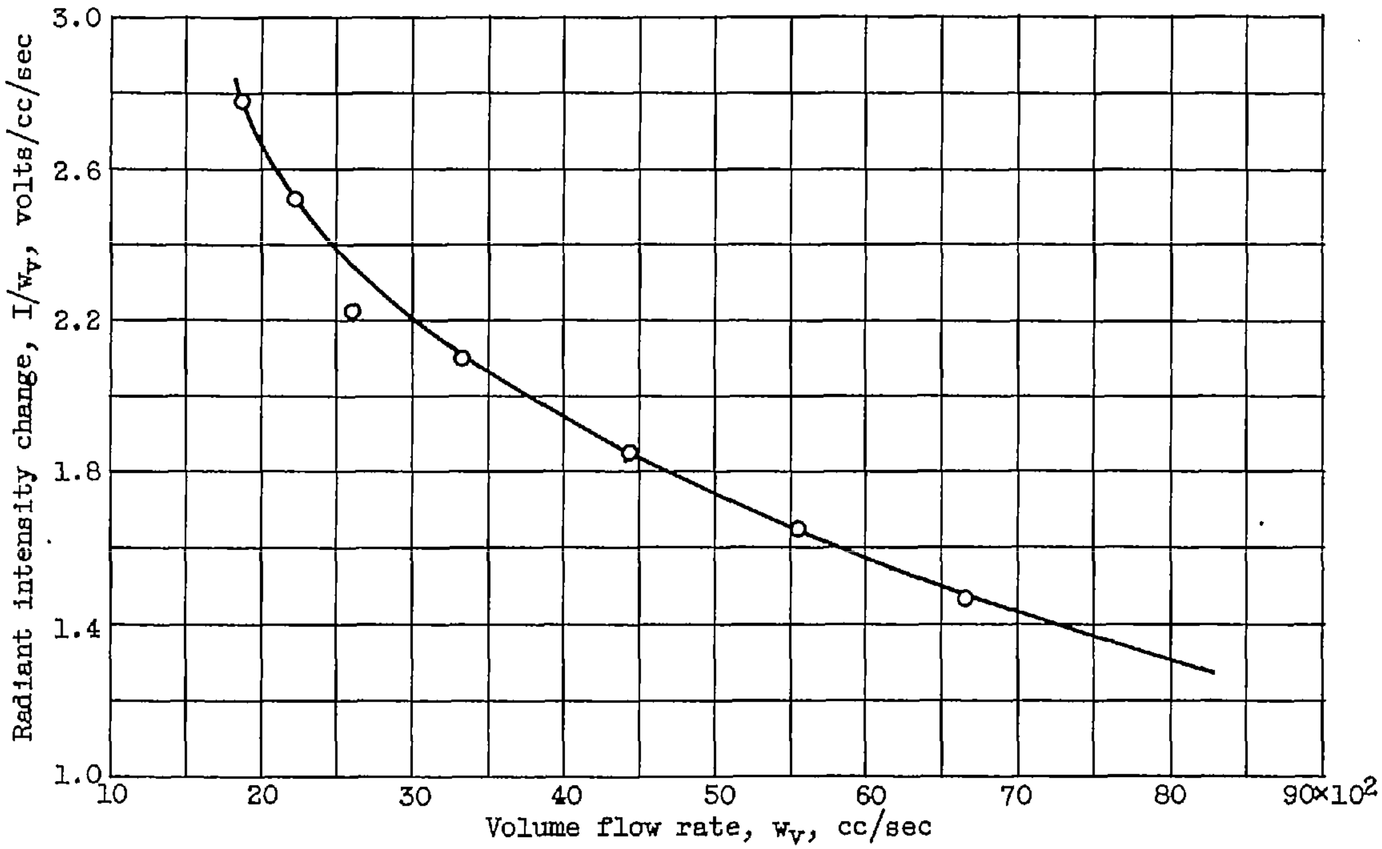


Figure 4. - Radiant intensity as a function of volume flow. Burner diameter, 0.930 centimeter.

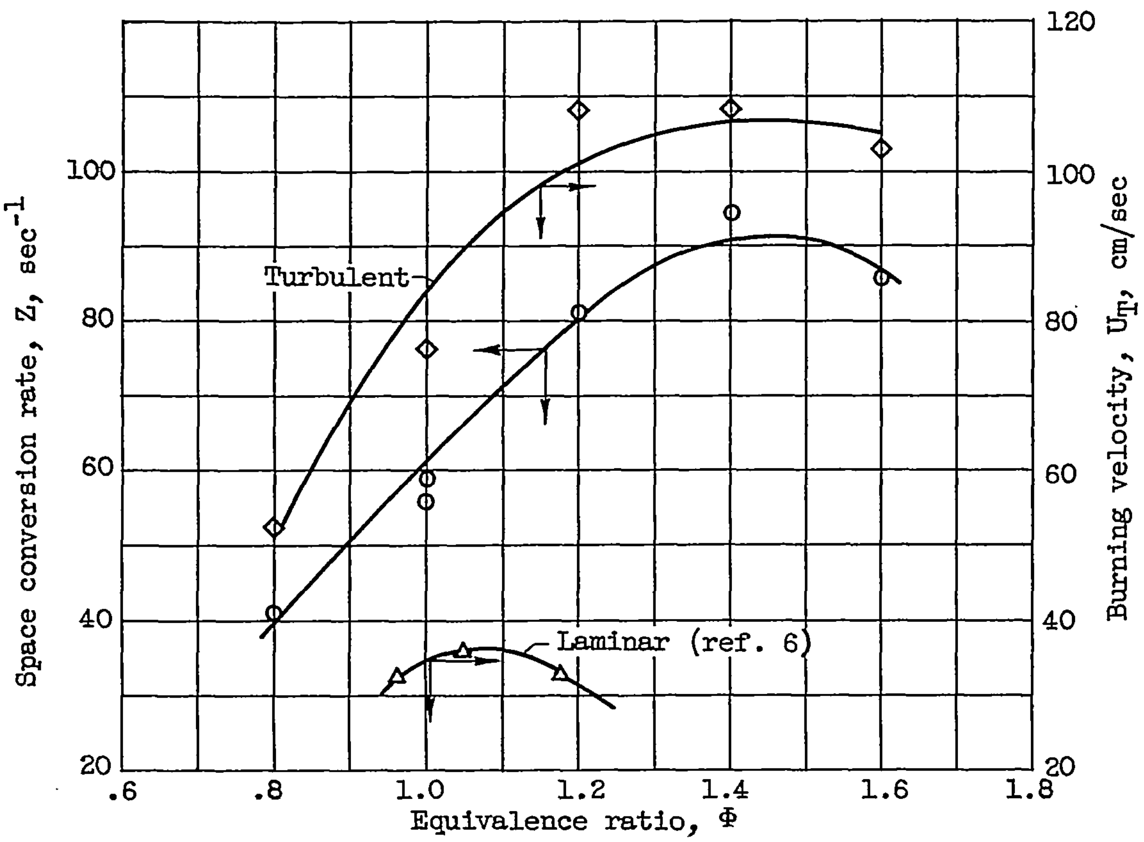


Figure 5. - Space conversion rate, turbulent burning velocity, and laminar burning velocity as functions of equivalence ratio; propane-air flames.

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